DRIYING CHARACTERISTICS OF HAY
ON A WAGON DRYING SYSTEM

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INTRODUCTION

"Forage is a product of relatively low market value in comparison with other agricultural products which are dried artificially. It is bulky, and has a high moisture content when cut. Unless such feed can be produced at a lower cost with an artificial drier than it can be produced by natural drying, or unless a product of much superior quality can be obtained, there seems to be but a limited field for artificial drying." (13) Although this statement was made 25 years ago, it still remains essentially correct.

Forage, as yet, cannot be dried at lower cost artificially than by natural means. However, today forage dried artificially does have a high market value due to its superior quality. Thus, one of two criteria involved has been achieved, and drying forage artificially seems not to be a limited field but appears to offer great possibilities to Agriculture.

To further illustrate this point, reference is made to the graph in the picture, Figure 1. In 1952 this farmer ceased feeding silage and started to feed artificially dried hay. Without essential changes in herd size, and without management changes, within four years production was increased approximately by 3600 pounds of milk per cow. These figures point out the contribution made to one farmer by artificially dried hay.

Weather controls haymaking more than any other one factor. By using a batch hay drying method, such as a wagon system, the farmer can handle smaller quantities and better predict his
FIGURE 1. Graph showing the increased production obtained by feeding top quality, artificially dried hay on Hominy Hill Farms, Colts Neck, N. J.
haymaking operations based on short periods of clear weather.

Heavy machine operations, such as baling, are very damaging to dry forage. The leaves of the forage tend to shatter (fall off) with rough handling, resulting in much of the leafy material, which contains great quantities of protein, being lost in the field. However, handling the material in a partially dry condition does little damage to the leaves, because the material in this condition is very tough. These facts point out another very important reason for drying forage artificially, which cannot be neglected when dealing with production of top quality forage.

With much research work being done on artificial drying, little is really known about the material itself, or the manner in which it acts when it is dried in its different forms. This project deals mainly with baled hay, with some information included about chopped hay. A form of batch drying, a wagon drying unit, was used for the experimental work. More emphasis will be given the thermodynamic processes involved in the drying cycle than to the physical characteristics of the wagon drying system.

STATEMENT OF PROBLEM

The purpose of this study is to thermodynamically analyze a wagon type, hay drying system.
REVIEW OF LITERATURE

"Drying is the removal of moisture to a moisture content in equilibrium with normal atmospheric air or to such a moisture content that decrease in quality from molds, enzymic action and insects will be negligible." (10) This statement made by Henderson and Perry points out the purpose for drying agricultural and other products. The necessity for drying lies in the fact that harvesting operations and weather conditions demand that the material be handled at a higher moisture content than safe for storage, as explained in the introduction.

Most farm products contain adsorbed moisture. This moisture exerts a vapor pressure that is dependent upon the type, nature and the moisture content of the material. (10) The ratio of the vapor pressure exerted by the material to the vapor pressure of free water at the temperature of the material is termed the equilibrium relative humidity. (10) This concept is important in the storage and drying of materials. By definition, the equilibrium relative humidity in practice would mean the following. If air is brought in contact with a product in storage that exhibits a lower equilibrium relative humidity than the air, then the product will take on moisture from the air. If the reverse is true, the air will receive moisture from the material. A material will exhibit a definite equilibrium relative humidity for a particular moisture content and temperature. Therefore, a plot of moisture content as ordinate and equilibrium relative humidity as abscissa would be valuable in learning more about
the material. This curve is called the equilibrium moisture curve.

(10) On page 278 in Henderson and Perry’s book, AGRICULTURAL PROCESS ENGINEERING, can be found equilibrium moisture curves for many agricultural products. (10)

Evaporation, as commonly known, is the change in state of water from a liquid to a vapor or gas. In drying, the observed relations concerning evaporation are to a great extent explainable on the assumption that a stagnant film of nearly saturated air persists at the surface. "Air flowing past the surface tears away the outer layer of film, which is replenished by evaporation of more water. The more rapid the flow of air, the thinner the film becomes, and the more rapid the transfer of water vapor into the air stream" (21)

When a current of atmospheric air enters an insulated duct or tunnel, containing a considerable amount of wet material and hence a large wetted surface area, the adiabatic transformations that occur are alike, or identical to the transformations that occur about a wet bulb thermometer, except that the scale is much larger.

The entire amount of air flowing is involved in the process and the material which has a great wetted surface acts as a large wet bulb. (6) A wet bulb thermometer normally is a mercury thermometer, covered or encased by a wetted sock. Due to the process of evaporation that occurs about the sock when subjected to an appreciable air flow, the temperature is depressed. Carrier (4) states that if a free wetted surface is affected only by the heated air, it will assume a definite minimum temperature. This temperature is defined
as the wet bulb temperature. (4) Although the state of the mixture is continually changed as it progresses through the material, the following is true. The dry bulb temperature will decrease, the dew point temperature will rise because the air will have received moisture; however, the wet bulb temperature remains substantially constant throughout the process. The process will tend toward saturation where all temperatures are equal. This process must be adiabatic for the wet bulb temperature to remain constant. If heat is added to the air from the material, or if heat is taken from the air by the material, the wet bulb temperature will no longer remain constant. "This fact forms the basis of all drying and air conditioning applications." (6)

Experiments at the Western Regional Research Laboratory show data which would indicate this to be true. A thermocouple was buried in a 3/16" thick carrot slice. The temperature of the slice and both wet and dry bulb temperatures of the air used for dehydration were recorded.

As seen by the curves plotted in Figure 1A, the temperature of the slice rose rapidly to the wet bulb temperature of the heated air. Initially the slice was at a high moisture content. During drying the temperature of the slice exactly equalled that of the wet bulb and remained at that temperature while about one-half of the total water was being evaporated and not until the end of the cycle did it migrate toward the dry bulb air temperature, as indicated by the graph.
FIGURE 5—RELATION OF TEMPERATURE OF MATERIAL TO TEMPERATURE OF AIR

FIGURE 1A. Graph showing heated air temperature, heated air wet bulb temperature and temperature of the sample, which was a 3/16" carrot slice being dried artificially.
The preceding graph would indicate two periods of drying. Henderson & Perry state that the drying process can be divided into two cycles. One is called the constant rate period, where the material acts like a large wet bulb. The second is called the falling-rate period. During this period, the drying process is governed not only by removal of water from the wetted surface of the drying material, but also by the movement of moisture within the material to the surface. (10) Practically all agricultural drying takes place in the falling-rate period. (10)

Moisture movement within the material takes place by a process called liquid diffusion. (10) The moisture is assumed to be brought to the surface by diffusion and there evaporated to a vapor. From the surface the vapor is then removed by the movement of air through the mass. (10). The rate at which this process progresses is determined by "the driving force", or the difference in moisture content at the surface and the equilibrium moisture content of the material at the state of the drying air. (10)

Hygroscopic materials (materials with bound water) contain moisture within the material that is held by certain chemical and physical forces. (5) This moisture is often called bound water and is physically held by the molecules within the material with the fixing mechanism called adsorption. (11)

The heat required to evaporate moisture down to 14% dry weight basis in wheat, a hygroscopic material, was found to be 1.00 to 1.06 times that required to vaporize water from a free water surface. (5)
Hygroscopic, as compared to nonhygroscopic materials, exhibit different characteristics regarding the drying rate, or removal of water per unit time. A nonhygroscopic material has a linear plot of weight versus time of drying. This indicates that the drying rate in lbs./unit of time is constant. The heat or energy required to evaporate the moisture was approximately the same as required for a free water surface; 1065 Btu/lb. of water evaporated as compared to 1051 Btu/lb. recorded in the steam tables for that particular temperature of drying. (5) Since hygroscopic materials as mentioned above require more energy, a nonlinear plot would be expected. (5) May being a hygroscopic material would have a drying rate curve similar to that for grain or corn.

Henderson & Perry (10) also point out that the velocity is important in the latter stages of drying. They state that temperatures and velocity are related in an equation with the velocity being raised to an exponent. The value of the exponent is an indication of the relative effect of internal diffusion as compared to surface resistance upon the drying rate. (10) By determining the value of the exponent, it will be determined what controls the drying rate, whether internal resistance to flow or resistance to vapor transfer at the surface. By knowing what controls the drying rate, better and more efficient methods of drying could be established by controlling factors which are most important in a particular stage of drying.

Evaluation of systems and design of equipment for processing operations, such as artificial drying, generally requires
information on three aspects of the basic process. (A) "The amount of energy required; (B) the rate at which the process may be made to proceed, (C) the extent to which the process may be carried, or the equilibrium point." (5)

The second point, as outlined by Dale & Johnson (5), was the most important consideration when use of heated air drying was initiated in hay drying. Old type mow drying systems didn't fit into the picture of farm operations with the modern baler. (20) The result was that batch drying came into being. These systems required speed of drying, and therefore, heated air was needed. (20)

"The several designs of wagon driers and the dock drier have resulted from the desire to eliminate labor." (20) Wagon drying is a special type of batch drying, in that small quantities of material are dried at one time utilizing the wagon itself as the drying structure. Wagon driers offer reduction in extra handling costs which are prevalent on stationary driers. Fineman (7) found that unit load handling methods reduce materials handling costs and that wagon drying offers maximum labor economy, but requires high initial investment in equipment.

Initially, wagon driers were designed without sides and equipped with an air chamber in the bottom. It was found that side losses were high because a small batch on a wagon had a very great exposure area for losses as compared to the small volume of material being dried. (20) Sides were then added to the wagon and corrugated to help reduce losses of air flow down to the sides. Schumacher (18)
reports that complete enclosure of the sides and ends of the wagon is required to prevent loss of useful drying air. Schumacher (18) also reports that the floor opening should be 50%; that is, 50% floor area and 50% open area in the floor. Drying in wagons was first accomplished by passing air up through the mass. Downdraft drying, that is passing air down through the mass, was developed when difficulty was encountered in drying the top layer of material in updraft drying. Bales tend to shrink and dry unevenly when the batch is small. The top layer of bales separates as drying progresses and dries slower than the lower, more compact layers thus prolonging the drying time. With downdraft drying, the top layer dries and shrinks first. Air now bypasses the top layer and must travel through the lower layers. These layers are still compressed because of the weight expressed upon them from the upper layers. (20)

In batch drying the principles of recirculation and reverse flow are extremely desirable. These are necessary because of the use of heated air and both tend to increase the efficiency of the drying process. (19)

MacKay (15) recommended a system to incorporate the principles of reverse flow and recirculation to increase efficiency. In 1953 this system, called a dual batch system, was designed and incorporated into the drying system of the Dairy Research Farm of the New Jersey Agricultural Experiment Station, Boontonville, N. J. Fineman (7) tested the installation in 1954. He found that by reversing the flow, using a single batch, that the drying time was reduced
from 25 hours to 18 hours for the same moisture content hay. He also
found that the weight loss distribution was more uniform. As pointed
out earlier, one disadvantage of single pass drying is that the layer
nearest the intake must be excessively overdried, to insure that the
last layer is dry. The reverse flow principle tended to eliminate
this condition. (7)

Recirculation is the reuse of exhaust air which is low in
relative humidity and contains much sensible heat. (19) This is es-
pecially desirable if exhaust is lower than outside relative humidity,
which occurs quite often in high temperature drying. Recirculation
was accomplished in the dual batch system by not exhausting the air
passing through nearly dry material direct, but passing the air
through another batch of wetter material and then exhausting it. This
insured that the exhaust air was near saturation at all times. (19)
Recirculation in a wagon system is utilized to reuse high temperature,
low humidity exhaust air. (19)

A characteristic of hay is that it is composed both of
leafy and stelmy material. (8) The leaf has a large surface area in
relation to its mass, and the stem has a small surface area in rela-
tion to its mass. The rate at which these two constituents dry out
differs greatly. (8) Thus not only do we have overdrying of layers,
but we have the condition where leaves are overdried in order to
insure that the stems are dry.
In high temperature dehydrators in England, there was a danger of scorching the leaves because they dried so much more quickly than the stems. (8) A machine called the mechanical lacerator or chopper is used to overcome this difficulty. This machine actually breaks down the cellular structure giving a free outlet to sappy cell content and provides a nearly uniform drying surface and an evenly-dried product. (8) In the United States, crushing is used in an attempt to obtain uniform drying as well as quicker pre-harvest field curing. Lawrence (14) found that the drying rate of stems was considerably increased by crushing, while the drying rate of the leaves seemed to increase very little. Chopping hay is also utilized in the United States.

Drying of chopped hay in wagons, as reported from Texas A. & M., was most efficient with heated air temperatures of 140°F to 150°F. (12) Tests concerning wagon drying of chopped hay were also run at Wisconsin. (2) When using high temperature drying air, it was found that air leaving chopped material 5 to 6 feet deep was nearly saturated even though high velocities of drying air were used.

Some spreading difficulties were encountered in filling the wagon with chopped material. (2)

Bruhn (3) reported that it was not advisable to run dry chopped hay through a high speed blower. The material near the entrance of the heated air was very dry, and excessive shattering of the leaves and separation of the product occurred.

The newest type of wagon drying is the dolly drying system.
One such system is now in operation in Pennsylvania. (9) This system incorporates the efficiency and low labor costs of wagon drying systems while also reducing the initial cost of the installation.

An automatic drier control system, as reported by General Electric (1) has been designed to control a drying system basing the control upon the fabric being dried. As mentioned before, in latter stages of drying, moisture must migrate from the inner fibres to the surface in order to be evaporated. This control modulates the heat supplied to match the rate at which moisture can migrate from the inner fibres. The control also adjusts the length of time according to the material being dried. (1) Once the properties of hay have been found, it would seem that this control system could be applied to drying agricultural crops.
METHODS AND EQUIPMENT

Thermodynamic properties of air are most useful in analyzing any drying process. Measurement of any two properties of the air is sufficient to determine all the other properties from the psychrometric chart. The most easily measured property of air is the dry bulb temperature. The other property normally measured is either dew point temperature or wet bulb temperature. Relative humidity, absolute humidity, specific volume, heat content, and vapor pressure, can all be determined from the psychrometric charts with the knowledge of two properties. To best analyze the drying process, the properties of the drying air must be measured before heating, after heating, and after exhausting from the material being dried. By following air through the entire process, we can determine the gain in absolute humidity, the quantity of heat added to the air by the heat exchanger, and heat loss or gain by the air to the drying mass.

In these experiments dry bulb temperatures and dew point temperatures were measured. These were recorded on a Foxboro multi-record temperature and dew point recorder which maintains a continuous record of these temperatures.

One dry bulb sensing element and one dewcell were placed at the air supply, another set in the plenum chamber to measure heated air properties, and another in the exhaust duct. The instrument was located inside the drying laboratory as shown in Figure 2. Long cables connected the instrument to the sensing elements located at
the drying site. The dew cells were shielded at each point to eliminate the adverse effect of high velocity air passing by them. Figure 4 shows the dew cell mounted in the exhaust duct.

Thermocouple observations of temperatures in the hay mass itself are of great value in determining the drying zone, and also flow patterns within the material. As the material becomes dry and removes less heat from the air to evaporate moisture, the temperature of the mass will slowly migrate toward the drying air temperature, because the heat received is used to elevate the temperature of the mass. The dry bulb temperature, then, at any point would be an indication of moisture content of the mass at a given moment. Two Brown 12-point Recording Potentiometers, also located in the drying laboratory (Figure 2) were used to record these temperatures as well as to record supply, heated, and exhaust air temperatures. Connecting thermocouple cables were run to the drying site through an overhead steel pipe to protect them from the weather. They were terminated in a junction box at the site, which afforded easy hook-up to the sensing cables located within the drying wagon.

A sling psychrometer and mercury thermometer were used at times to check the instruments.

Moisture determinations were made by using the gravimetric method. Samples were taken from several bales in the field and immediately weighed and placed in the oven. The dry weight of the samples was usually between 1,000 and 1,500 pounds. The sample was usually dried in an oven at 200° F. for approximately 24 hours,
FIGURE 2. Drying laboratory showing the Foxboro multi-record temperature and dew point recorder and the Brain 12-point recording potentiometers. Connecting cables were run from the drying site to the instruments in the laboratory.
or until three successive weighings yielded no change in weight. Wagon weights were taken on a large platform scale both before and after drying. In some cases the wagon was weighed at four hour intervals during the drying cycle, to help determine the drying rate of the material and to check heat and mass energy balance calculations.

Fuel consumption rates were determined by a weight rather than a volume method. A fifty gallon drum was mounted in a frame and placed upon a platform scale. Fuel flowed by gravity from the drum to the oil pot of the crop drier. A small pump was provided to pump the fuel from a larger storage tank into the weighing drum. At the time drying was started, the scale was balanced and the weight recorded; when drying stopped, the weight was again recorded. Since differences in weights were used, any errors of the scale could be minimized.

Air flow through the material being dried is of most importance in drying studies. Air flow was controlled in these experiments by a large damper located between the heat exchanger and the heated air plenum chamber, Figure 3. With the type of crop drier used in this experiment, controlling the air flow by the damper located in the plenum chamber actually controlled the temperature rise or increase in temperature of the outside air since the fuel flow was kept constant. Therefore, the damper was used indirectly to give a desired temperature rise to the supply air.
FIGURE 3. Air flow damper located in housing between crop drier and heated air plenum chamber.
Air flow measurements were made by using a specially designed exhaust duct with an orifice plate located at discharge, see Figures 4 and 5. This duct was patterned after the plenum chamber duct used by Great Lakes Steel Corporation's Research, Development, and Quality Control Department in their research on a grain drying system. (17) An orifice is a device used to measure fluid flow by simply measuring the difference in pressure on either side of the orifice plate opening. Knowing the orifice diameter, the properties of the air, and the pressure differential, the air flow can be determined. The derivation of the equations used will be illustrated in the sample calculations section. The coefficient of discharge for this orifice was not calculated by calibration, but a value of .68 was used in all the air flow calculations. (16)

Pressure measurements in the duct and in the heated air plenum were made by using an inclined manometer coupled to an air gage. All the pressure tap connections were terminated in the air gage, and readings were taken by simply rotating the valve mechanism.

The system was made completely air-tight by enclosing the bottom of the drying wagon with a tough, nylon-canvas material creating another plenum chamber beneath the wagon. An 18" x 72" opening centered in one side of the canvas offered the avenue of exit for the exhaust air. A sheet metal coupling was attached to the canvas and used to connect the canvas plenum to the two exhaust ducts. The canvas was attached permanently to the wagon utilizing gasket material to effect an air-tight seal. Sown in the bottom of the canvas was a
FIGURE 4. Exhaust ducts in place. Dew cell and temperature bulb are located in the side of the duct, with the air gage and inclined manometer resting on the duct. Hose connections run from the pressure taps to the air gage.
garden hose. To seal the canvas to the floor of the drying site, this hose was placed in a notched 2" x 4" which was nailed to the lumber embedded in the concrete. Another 2" x 4" was then clamped tightly to the notched 2" x 4" compressing the garden hose in the notch and forming an effective air seal.

DESCRIPTION OF THE EXPERIMENTAL DRYING UNIT

The experimental drying unit was of the downdraft type with only provisions for one wagon. A plywood plenum chamber was used to receive heated air from the heat exchanger and pass it through the material. Figures 6 and 7 show the overall installation.

The plywood chamber was supported by cables with pulleys mounted to a sturdy wooden framework, as shown in the diagram in Figure 6. When in the drying position, however, the plywood chamber rested upon the wagon. A gasket material was used to effect an airtight seal and special clamps were used to secure the plenum chamber to the wagon. These clamps were patterned after those used by a farmer in Pennsylvania.

The separating force created by the internal pressure was greater than the weight of the chamber, creating the need for sturdy, yet easily attached, clamps.
FIGURE 6. Experimental wagon drying site. Crop drier is located at the left with the large fuel storage tank. The heated air plenum is seen supported by cables on the wooden superstructure.
Figure 7. EXPERIMENTAL WAGON DRYING SETUP
Figure 8 shows the exhaust plenum sealed in place and the heated air chamber being lowered into the drying position.

The heat exchanger used was a Pierson-Moore Crop Drier with a pot-type burner capable of consuming 3 gallons of No. 1 fuel oil per hour. The air supply was furnished by a 32-inch propeller-type fan mounted on the crop drier. The fan was powered by a 5 HP motor capable of delivering 16,000 cubic feet per minute at a static pressure of one inch of water.

The wagon itself was nominally 8' x 16' with 5 feet sides and an inside floor area of 115 square feet. The floor was constructed of 1 1/4" x 1 1/4" T-beams on 2 7/8" centers, giving an approximate floor opening of 50%. Sides on the wagon were corrugated to help decrease air losses along the walls. As mentioned earlier, the wagon was equipped on all sides with a continuous canvas plenum chamber for sealing the system.

The floor of the drying site had concrete runways for the wagon wheels, with two 4" curbs used to position the wagon. 2" x 4" lumber was embedded in the periphery of the concrete with dimensions such that they approximated an 8' x 16' rectangle. The V-notched, 2" x 4" boards used in sealing the canvas to the floor were nailed to the boards embedded in the periphery of the concrete.
Figure 8. Heated air plenum being lowered into drying position on top of the wagon. The canvas exhaust plenum is shown in the sealed position.
Baling was accomplished with a New Holland 66 twine-type baler. However, one or two runs were made with an International Harvester baler. The material was not crushed but was talced several times before being raked into the windrow with a conventional side delivery rake, which could either ted or rake. The wagon was towed behind the baler, and bales were positioned for drying with thermocouples inserted in the proper location as leading progressed.
SAMPLE CALCULATIONS

Determination of higher heating value of fuel oil used:

Specific gravity was determined by a hydrometer equal to .99

\[
\text{DEGREES API} = \frac{141.5}{\text{Specific Gravity}} - 131.5 = \frac{141.5}{1.019} - 131.5 = 41.30
\]

Higher heating value:

\[
\text{HHV} = \left(18.010 + 57.5 \times \text{API} \right) - \left(0.35 \times \text{API}^2 \right) \text{ IN BTU/ lb}
\]

\[
18.010 + 2380 - 597 = 19.793 \text{ BTU/ lb of fuel}
\]

Specific weight:

\[
\text{SW} = 62.4 \text{ lb/ft}^3 \times \frac{1 \text{ ft}^3}{7.48 \text{ gallons}} \times \text{Specific Gravity}
\]

\[
\text{SW} = 6.82 \text{ lb/gallon}
\]

British Thermal Units per gallon of fuel

\[
19.793 \times 6.82 = 135000 \text{ BTU/Gallon}
\]

Determination of equation for calculating air flow:

\[
Q = \text{Air flow} = C_0 A V \text{ WHERE } V = \sqrt{2gk h}
\]

\[
C = \text{Coefficient of discharge}
\]

\[
A = \text{Area of orifice in square feet}
\]

\[
h = \text{height in feet of fluid flowing, } h = \frac{P}{\omega}
\]

\[
V = \sqrt{\frac{2}{\text{sec}} \times 32.2 \text{ ft}^2 \times 3600 \times \rho \times 62.4 \times \frac{1}{12} \times \frac{1}{\omega} = \frac{\text{ft}}{\text{min}}}
\]

\[
Q = 1096 \times \omega \times A \sqrt{\frac{P}{\omega}}
\]

from Marie's (16) \[
\frac{D_2}{D_1} = 0.6 \quad C = 6.8
\]

Where \( P \) = pressure in inches water

\( \omega \) = specific weight of gas
A portion of the run of October 10-11 will be analyzed. Heat was applied at 1450 hours and stopped at 1850.

Heat weights:
\[1450 \quad 3820\]
\[1850 \quad 3410\] Pounds Water removed.

Fuel consumption:
\[1450 \quad 410\] \[1850 \quad 378\] Pounds of fuel used.

Fuel flow rate:
\[72 \times \frac{1}{6.82} \times \frac{1}{4} = 2.64 \text{ Gallons per hour} \]

Air flow:
\[Q = 1096 \times C \times A \times \sqrt{\frac{P}{V}}
\]
\[= 1096 \times 6.8 \times 1.765 \times \frac{0.12}{0.761} = 1655 \text{ CFM for each orifice} \]
\[= 3310 \text{ CFM} \]

\[\frac{3310}{115} = 29 \text{ CFM/SQUARE FOOT OF FLOOR} \]

\[\Delta T = 38^\circ F \]
\[\text{HEAT} = \text{MasseXP specific heat } \times \text{ Temperature rise} \]
\[= \frac{3310}{13.4} \times 24 \times 38 = 2250 \text{ BTU/Min} \]

Heat added to air also = Column 11 = 909 BTU/lb

Heat = \[\frac{3310}{13.4} \times 9.09 = 2241 \text{ BTU/Min} \]

Heat energy supplied to the heat exchanger.
\[\text{Heat} = \text{Flow Rate} \times \text{HHV} \]
\[= \frac{2.64}{60} \times 135,000 = 5930 \text{ 13BTU/Min} \]

Efficiency of the burner.
\[\text{Overall Efficiency} = \frac{Q_{in}}{Q_{out}} = \frac{2250}{5930} \times 100 = 38.1\% \]

Observed Data were taken from Field Data Sheet.
Thermodynamic analysis of air entering and leaving the mass.

By determining the absolute humidity of the supply air, in grains per pound of dry air, and then determining the exhaust absolute humidity, and getting the difference between these two quantities we can determine the moisture removal rate. This figure would be represented by column 26 on the data sheet, that is the difference in absolute humidity, and the moisture removal rate would be found in column 27. Column 31 represents the amount of heat lost by the air in column 29 plus or minus the heat added or subtracted by the heat mass, this figure being found in columns 25 and 29. Column 38 represents the heat actually available for drying, that is the wet bulb depression plus or minus the loss in column 25. The ratio of column 31 over column 38 is defined as the true thermal efficiency.

By multiplying the heat used in evaporation, column 31, by the mass flow rate we can determine a value of BTU used per minute for evaporating moisture. Dividing this quantity by the removal rate in pounds per minute, column 27, we can now determine a value for the amount of heat utilized per pound of water evaporated. The same calculation can be made for the heat supplied to the air.

**Moisture Removal Rate**

**Average Value for Column 26:** 46.1 Grains/pound of dry air.

\[
\frac{46.1 \times 3310}{7000} = 1.63 \text{ pounds water/ min}
\]

\[
1.63 \times 4 \times 60 = 391 \text{ Total pounds removed.}
\]

This compares with 410 pounds found by

\[
\frac{191.7 \times 4 \times 60}{163} = 410 \text{ pounds}
\]
COLUMN 31 shows 6.01 Btu/lb used

\[ \times \frac{3310}{13.4} = 1485 \text{ Btu/min} \]

Dividing by drying rate \( \frac{1485}{1.63} = 920 \text{ Btu/lb water} \)

Heat supplied drying air: 2250 Btu/min

\[ \frac{2250}{1.63} = 1380 \text{ Btu/lb water evaporated} \]

Column 31 divided by column 38

Yields thermal efficiency of 77.2%

Moisture determination:

Wet weight

\[ \text{Wet weight of sample} = \frac{3.220}{1.410} = 2.28 \text{ pounds} \]

Bone dry

\[ \text{Bone dry} = \frac{2.28}{1.410} = 1.6 \text{ pounds} \]

Moisture content wet basis = \( \frac{2.420 - 1.410 \times 110}{2.420} = 41.6\% \)

Moisture content after 4 hours = \( \frac{(41.7\% \times 2520) - 410}{3410} = 35\% \)
<table>
<thead>
<tr>
<th><strong>Psychrometric Chart Values</strong></th>
<th><strong>195</strong></th>
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<tr>
<td><strong>Pounds of water evaporated per minute</strong></td>
<td><strong>25</strong></td>
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<tr>
<td>Column 8-20</td>
<td><strong>25</strong></td>
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<tr>
<td>Specific heat of air, .24 x Column 28</td>
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<td>Column 25</td>
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<td>Wet Bulb Temperature **</td>
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<td>.24 x Column 35</td>
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<tr>
<td>Efficiency Percent 31/38 ****</td>
<td><strong>17.2</strong></td>
</tr>
</tbody>
</table>
FIELD DATA SHEET

Type of Hay ALFALFA  Date OCTOBER 10, 1956

# Cutting THIRD

Gross Weight of Wagon and Hay 6365 lbs.
Tare Weight 2545 lbs.
Wet weight of hay 3820 lbs.
Fuel weight 450 lbs. Scale reading in lbs.

Time 1800

Temp. Readings

1. (outside)  
   Drybulb 52 °F.  Foxboro  
   Drybulb 53 °F.  Brown  

2. (plenum)  
   Drybulb 90 °F.  Foxboro  
   Drybulb 91 °F.  Brown  
   Dewpoint 28 °F.  

3. (exhaust)  
   Drybulb 68 °F.  Foxboro  
   Drybulb 69 °F.  Brown  
   Dewpoint 54 °F.  

Pressure Readings in inches of water:

Plenum

Exhaust ducts (top tap .12 .12  
   (side tap .12 .13)
INTERPRETATION OF RESULTS

Data for all the runs were taken from the recording instruments and transposed to large data sheets for analysis. Weights and pressure readings were taken from the field data sheets used for each run. Pertinent data were plotted to give a visual picture of the processes involved. All of the graphs were plotted to show the progression of events with time. The Army system of telling time was used to avoid confusion with dates. For example, 2000 hours is 12 plus 8 or 8:00 P. M. 0400 hours would be 4:00 A. M. An attempt will be made to report on each run individually at first and then to compare the runs collectively.

Discussion of Curves

The run on October 16 and 17 was made with alfalfa-grass hay as the material to be dried. It was third cutting with a varying moisture content because of the difference in growth in the field. The hay was mowed on the morning of the 15th and baled on the afternoon of the 16th. This hay, as well as all the other material used in these tests, was not crushed but tedded several times during the field curing period and raked just prior to baling.

The average temperature rise of the supply air was 42° F. with a total air flow of 2760 CFM or 24 CFM per square foot of floor area. The average moisture content at the start of drying was 38% and at the end was 15%. Two or three dense bales which had not dried were noted on the bottom layer when unloading.
A description of the entire run will be made by analyzing the five graphs which give the most information regarding the drying cycle.

The plot of relative humidities versus time, Graph #1, shows the effect of the diurnal cycle upon the drying process. The supply air relative humidity increased rapidly as cooling occurred in the evening nearly reaching saturation at 0200 hours on 17 October and remained constant until rapid warming occurred at 0800 hours. Although this phenomenon is unusual in autumn in New Jersey, it is typical in the summer, unless there is an air mass change due to front movements during the night. The dew point will remain relatively constant as evapotranspiration decreases. The dry bulb temperature will decrease, resulting in high relative humidity during the night.

The heated air relative humidity did not rise over 25% even though the supply air was over 90% for a long period of time. The heated air relative humidity tended to dampen the exhaust relative humidity curve.

The exhaust relative humidity dropped quite rapidly during the early part of the run but slowly leveled off and remained nearly constant during the night when the outside relative humidity was high, and dropped off again in the morning as the outside humidity decreased sharply.

From 0200 hours through 0800 hours, the exhaust relative humidity is nearly 40% lower than the outside air relative humidity. This would indicate that high temperature, low relative humidity air
is being wasted. Partial recirculation of this air would help to
increase the efficiency of the cycle. Outside air at $55^\circ$ F. and 90% 
relative humidity was a heat content of 22.0 Btu per pound. Exhaust 
air at the same time has a temperature of $80^\circ$ F., a relative humidity 
of 50%, and a heat content of 30.8 Btu per pound. Air having differ-
ent properties mixes along a straight line drawn on a psychrometric 
chart between the two points which define the conditions of the mix-
ing air. The position along this line is dependent upon the mass 
flow rates of the two quantities of air. In this case, assuming 
equal flow rates or 50% recirculation, the point would fall at the 
median.

The resulting mixture temperature would be $65^\circ$ F. and the 
relative humidity would be 67%. This would increase the heated air 
temperature to approximately $100^\circ$ F. and, even though more water is 
present in the air, the ability of the air to hold moisture has in-
creased and the relative humidity of the heated air would be reduced 
to 10%. This cycle will continue to repeat itself. The heated air 
temperature will rise, the exhaust air temperature will also increase, 
resulting in another increase to the heated air temperature. This 
process will continue until the high temperature control on the crop 
drier modulates the flow of fuel and maintains a maximum temperature, 
resulting in lower fuel costs.

Graph #2 shows the variation of the temperatures with time, 
within the mass as well as the heated, exhaust, and outside air 
temperatures. The thermocouples were arranged in a vertical column
in the center section of the wagon. The legend on the graph shows the exact location of the thermocouples in the mass.

Thermocouple #8, located within 6 inches of the heated air plenum chamber, showed a very sharp temperature increase when drying was started, indicating that drying occurred very rapidly in the top 6 inches of the load. Initially, the material receives heat energy which is used for evaporating moisture, approximately 1000 Btu's for each pound of water evaporated. As the moisture content of the material decreased with drying, less and less water becomes available, and some of the heat energy received is used to elevate the temperature of the material. The rate at which the temperature of the mass increases then indicates the speed of drying. For a more complete explanation of this, see Mackay. (15)

Thermocouple #7, located 6 inches below #8, dried at approximately the same rate as #8 only lagging by approximately 45 minutes. Thermocouples #5 and #9 show a similar pattern only move out together. The slope, that is temperature change per unit time, is slightly less for #5 and #9 than it was for #7 or #8.

The next section of hay to dry is in the top of the bottom layer, which dries more quickly than the bale above it represented by #10. Although #6 is cooler than #10 for the first five hours, it shows a definite point when the temperature starts to increase. However, it does not increase immediately to the heated air temperature. The curve is dampened somewhat by the reduction of the heated air temperature during the night.
Thermocouple #10 shows no signs of a definite upward surge as the other bale temperatures do, but gradually approaches the temperature of bale #6.

Thermocouple #12 was in the bottom 6 inches of the bottom bale. Number 12 was probably located in a very dense section of the bale. This can be deduced by noticing that at the start of the drying cycle its temperature was nearly $10^\circ$ F. higher than the other bales. This was due to the heat of respiration of the hay which had been raising the temperature of the mass since it was baled and during the time it was loaded, waiting until drying started. The temperature decreased rapidly as heated air was applied to the load, and paralleled the outside temperature and wet bulb temperatures, being approximately $15^\circ$ F. warmer than the outside temperature. The bale was still wet when the wagon was unloaded. A few other bales were also found to be too wet to store. They occurred, however, only in the bottom layer of bales.

At any time during the run, the temperature rise added to the supply air by the exchanger can be quickly found by observing the distance between curves 1 and 2. These curves, of course, follow the diurnal cycle. It would be possible to eliminate the variability of the heated air temperature by using a variable-flow device which would sense heated air temperature and modulate the fuel flow to adjust for the outside air depression which occurs during the night.

Curve #3 defines the exhaust temperature at any time. The difference between curves 2 and 3 at any moment would indicate the
amount of heat given up by the air to the mass. This heat energy may be used for evaporating moisture or for elevating the temperature of the hay mass. Assuming adiabatic drying for the present, then the difference between curves 2 and 3 would be an indication of the heat used to evaporate moisture. The maximum amount of heat which is available for drying is represented by the difference between curve 2 and the wet bulb temperature line, since the wet bulb temperature would define saturation. A thermal efficiency can be determined representing the amount of heat utilized compared to the amount available.

Mackay (15) defined true thermal efficiency as the ratio of heat used for drying to the heat available.

The heat actually available for drying is the specific heat of air times the temperature depression between heated air dry bulb and wet bulb temperatures, plus or minus the heat content change of the drying air.

The heat actually utilized for drying is the specific heat of air times the temperature depression between heated air and exhaust air temperature plus or minus the heat content change of the drying air.

For an approximation of the true thermal efficiency at any time during the run, a ratio of the differences between curves 2 and 3 to the differences between 2 and the wet bulb, multiplied by 100 would give a satisfactory value. For example, at 2400 hours the
value calculated by the above method is 49.2%, the value on the thermal efficiency curve at this time is 51.5%.

Graph #3 shows the thermal efficiency curve for this run. Initially the efficiency was high but fell off quite rapidly as moisture became less available. Methods used to determine the true thermal efficiency are shown in the analysis of data and sample calculation sections, included in this report.

Graph #4 shows the drying-rate curve. The falling rate period of drying is clearly indicated in this graphic presentation of the drying rate. Initially, the moisture removal rate was nearly two pounds of water evaporated per minute, but in less than four hours the rate had been decreased almost by half. The rate decreased more slowly during the next few hours and then, from 0400 hours to 0800 hours, was decreasing slightly. At 0800 hours, however, the supply air temperature rose sharply as did the heated air temperature. This increased the temperature of the hay mass and speeded up the drying rate, as shown on the graph, between 0800 and 1000 hours. This would tend to indicate that during later periods of drying, when internal moisture movement controls the drying process, temperature of the drying air is the most important factor in the system, since this was the only quantity changed.

Graph #5 indicates how the energy supplied to the mass is utilized. The actual heat used to evaporate moisture from the material is approximately 1000 Btu's per pound of water evaporated. It was difficult to determine any trends in the data, but it did
Indicate that the energy required was essentially constant over the
normal range of drying associated with hay. The top curve indicates
the heat which is supplied to the air by the heat exchanger, per
pound of water evaporated. Initially, when drying was more efficient,
all the heat was used to evaporate moisture. This is shown by the
low values of the Btu's required per pound of water evaporated. How-
ever, as drying progressed, the Btu's supplied per pound of water
increased almost at a constant rate and then gradually leveled out
toward the end of the cycle, when drying was increased slightly by
the increase in heated air temperature. Near the end of the cycle,
the heat was being used to elevate the temperature of the hay mass,
to evaporate some moisture, and the remainder, neglecting radiation
losses, was being lost in the high temperature exhaust air. At the
start, 1250 Btu's were supplied to the air per pound of water
evaporated; while near the end of the cycle it increased to nearly
5000 Btu's. The amount of heat actually supplied to the burner per
pound of water is over twice that much. To determine the actual
amount of heat supplied to the burner, simply divide the quantity
on the upper graph by the overall burner efficiency. The overall
burner efficiency was determined by measuring the fuel used and
measuring the air flow past the exchanger and the temperature rise
of the air.
The ratio of these two defines the overall burner efficiency. This means that at daybreak, with a calculated burner efficiency of 45%, the actual amount of heat supplied to evaporate one pound of water is 13,000 Btu's. This means that over ten times the energy actually utilized for drying was supplied.
Graph showing heat supplied and heat utilized in evaporating moisture.

- O-O - Heat supplied to air
- □□ - Heat used in evaporation

Time in Hours:

- 1500
- 1800
- 2100
- 2400
- 2700
- 3000
- 3300
- 3600
- 3900
- 4200
- 4500
- 4800
- 5100
- 5400
- 5700
- 6000
- 6300
- 6600
- 6900
- 7200
- 7500
- 7800
- 8100

Heat per pound of water evaporated.
RUN - October 9-10

For the run of October 9-10, third cutting alfalfa hay was used. The bales were quite uniform and of approximately equal moisture content with the average before drying being 32.4% and the average after drying, 10%. The hay was moved on the afternoon of the 8th and baled on the afternoon of the 9th. The average temperature rise of the outside air throughout the run was 48°F., with an air flow of 2920 CFM total or 25.4 CFM per square foot of floor area. Air flows of this magnitude are quite small, being approximately 0.3 miles per hour through the hay mass.

Graph #6 shows that variation in relative humidities are similar to the preceding run. The supply air relative humidity increases sharply when cooling begins at night and is relatively constant for the major portion of the night, decreasing sharply as heating occurs in the early morning. The heated air relative humidity remained essentially constant throughout the night, being influenced by the low supply relative humidity, but more so by the high dry bulb temperature of the heated air. The exhaust relative humidity decreased uniformly throughout the night defining a smooth curve. An important feature in this run is that the heated air relative humidity was constant, leaving the exhaust relative humidity curve free from any dampening which might be produced by diurnal fluctuations. Except for a slight temperature depression during the cool of the night, it can be seen that the drying cycle was nearly divorced from outside conditions, at least as far as relative humidity is concerned, by the use of high temperature heated air.
The difference between the exhaust curve and supply curve again points out the real need of reusing the high temperature exhaust air.

The reverse slope of the exhaust relative humidity curve between 0800 hours and 1000 hours indicates that the relative humidity was decreasing more rapidly than during the night. This was caused by a rapid increase in outside temperature which caused the drying air temperature to increase. The exhaust air temperature increased at the same rate as the heated air, resulting in a lower exhaust relative humidity.

The temperature curves, Graph #7, indicate that the load was fairly uniform in nature. The same general trends were indicated on this curve, as explained in the previous run. Number 10, although above number 12, dried at a slower rate possibly indicating a dense mass at that point in the load. Although the layers dried in sequence - 8, 9, 7, 12 - the rates at which they dried, or the slope of the curve during the time they rise to the heated air temperature, decreased from top to bottom.

The thermal efficiency curve, Graph #8, indicates a rapid falling off early in the run and a more gradual falling off during the latter stages. However, at 0900 hours the curve showed a slight increase in efficiency. Noticing that the temperature rose 15°F during this period, and that the material was extremely dry at this point, it again seems that high temperatures control the internal movement of the moisture within the material.
The drying rate curve, Graph #9, as expected, showed the identical characteristics exhibited by the thermal efficiency and exhaust relative humidity curves. The slight upward trend at the end of the cycle was caused by the rapid increase in heated air temperature.

By using the drying rate curve, a true mean moisture removal rate could be determined by mechanical integration or by using a logarithmic mean value. The final average moisture content of the hay mass after drying was approximately 10%, indicating that unnecessary drying had occurred. Let us assume for the present that a desirable average moisture content of the mass would be 15%, in order to insure that the bottom layer is at least below a moisture content of 20%, a safe storage level. The required moisture to be removed would then be 590 pounds instead of 700 pounds removed over the 17-hour period. Using the log mean removal rate value, the drying time required to reach 15% would be 13 hours. We must now go back to the drying rate curve and adjust the log mean value for the shorter drying period. The new value gives a drying time of only 12 hours. Repeating the process until the actual time involved is found gives a time of approximately a little less than 12 hours. The temperature curves, Graph #7, indicate that all the bale temperatures have reached the heated air temperature at this time except number 10 which is 40°F less.
The exhaust temperature at this point is 90°F below the heated air temperature. This confirms the fact that the mass would be dry at that point and would tend to lend weight to the accuracy of the drying rate curve.

The drying process could have been stopped five hours sooner with savings of nearly one-third the total fuel cost.

If a drying rate curve could be determined for the material under specified conditions, it could be used to determine the time required to dry a particular moisture content hay mass to a safe storage level. This would be invaluable in eliminating much of the guesswork in determining the proper time to stop drying. Perhaps another more simple indicator could be used, that being the temperature of the exhaust air. When the exhaust temperature rose to within a certain value of the heated air temperature, the material could be assumed dry. The value for this depression in this run was 10°F.

Graph #10 shows the variation of Btu's required per pound of water evaporated with time. Again it is seen that the heat required to evaporate the moisture is essentially constant throughout the drying process with the normal range of moisture contents involved in hay drying. The slight increase at the end of the cycle indicates that at extremely low moisture contents more energy is required, but this cannot be substantiated on such little information.
Graph 6. October 9 - 10. Curve showing change in relative humidity with time.
Graph 8. Thermal Efficiency

October 9 - 10
Alfalfa
Third Cutting
Moisture Content 32.4%
Average Temperature rise 48°
Air Flow 2920
or 25.4 CFM per square foot floor
Graph 10. October 9 - 16

Graph showing heat supplied and heat utilized in evaporating moisture.
The heat supplied per pound of water evaporated increased rapidly at first, and then increased more gradually during the remainder of the run. Maximum values are quite high because the material was dried to such a low moisture content. At 0500 hours the supplied heat to the drying air was approximately 5000 Btu's per pound of water evaporated. The moisture content at this time was determined to be 15% which agrees with the run of October 16-17. It also showed a heat requirement of 5000 Btu's per pound at 15% moisture content. To find the total heat supplied to the hay we must again divide by the burner efficiency.

**RUN - October 10-11**

The run of October 10-11 utilized third cut alfalfa taken from the same field that the material for the run of October 9-10 was taken. The moisture content was approximately 42%, somewhat higher than the previous run because of a shorter field curing period. The average temperature rise for the entire run was 38°F with an air flow of 3310 CFM or 29 CFM per square foot of floor area.

Wagon weights were taken every four hours during the run explaining the breaks observed in the curves after every four drying hours. The average moisture content at the end of drying was 15%.

The relative humidity curves, Graph #1111, show characteristics, except for the exhaust relative humidity curves, similar to the two preceding runs discussed. The exhaust relative humidity curve decreased uniformly as would be expected until drying was stopped, following the first four hours of drying. After weighing
the wagon, it was again returned to the drying site and drying started once more. The exhaust relative humidity now exhibited a marked increase of 3%. However, it fell gradually and within one hour was again below the value observed before drying had stopped. The same events occurred following the next four-hour period of drying. The increase was again approximately the same with the time lapses between stopping and starting about equal. Following the third and fourth four-hour periods, the value again was higher than before stopping but decreased more rapidly than the first two four-hour periods. Following the fifth four-hour period, the relative humidity increased nearly 6%, or twice as much as before, but dropped off even more quickly.

The explanation of this phenomenon centers about the movement of moisture within the material, and removal of moisture from the exposed surface of the material. Stopping the drying process obviously stopped the removal of moisture from the exposed surface of the material. However, the internal movement of moisture did not cease but continued to progress and deliver moisture to the outside walls of the material. Then, when drying was again started, there was more moisture available at the surface of the material. More cooling occurred because of greater evaporation, and this depressed the exhaust air temperature and increased the exhaust relative humidity.

This is perhaps even more graphically portrayed by the temperature curves, Graph #12. After the first four hours of drying, the top layer, which is represented by 7 and 8, is already dry; but
the second layer, represented by 5 and 9, is still drying. When drying was stopped at 1800 hours for weighing, number 5 was reading 80°F, and number 9 reading 75°F. However, immediately upon restarting the drying process, the temperatures were depressed approximately 5°F. On the surface it might appear that the depression was caused by the hay mass cooling, while the wagon was in transit to and from the scale. However, the temperatures were not depressed until after the heated air was passed through the material. This can also be substantiated by observing the top layer represented by numbers 7 and 8, which exhibited no cooling, and also by the bottom layers which showed no change since they had not yet begun to dry. Therefore, the cooling of the material was accomplished by removing heat from it to evaporate the additional moisture now present at the surface of the material. The temperatures, however, rose rapidly to their former value with the rise being dampened somewhat by the falling temperature of the heated air. After four more hours of drying, the same pattern occurred but with smaller temperature depressions. The bottom two layers still showed no indication of a depression. Following the third four-hour period, the top layer and the second layer were completely dry but the third layer, represented by number 4, showed a slight depression. Number 10 indicated no depression. At 0800 hours, the end of the fourth period, number 4 again exhibited a decrease with 10 not showing any response as yet. The exhaust temperature was affected by the rapidly rising heated air temperature at this point and did not show any depression. At 1200 hours, numbers 3 and 10 showed a very slight depression.
The thermal efficiency curve, Graph #13, also illustrates the phenomenon noted at the weighing intervals. The efficiency was noted to increase immediately after commencing the drying operation but to decrease rapidly again within approximately one hour. The curve appears to be of the same general form as the preceding runs, but at each interval it is elevated slightly and shifted to the right, which would tend to make the end efficiency appear higher.

Graph #14 shows that for the first three hours the drying rate was essentially constant. The rate dropped sharply after three hours and continued to drop throughout the remainder of the run, trailing off sharply at the end of the cycle. This curve does not seem to be affected by the weighing intervals, except perhaps to flatten it at the center during the early morning hours. The drying rate curve was used to calculate a weight-loss curve, Graph #15, for the material since an actual weight-loss curve was determined from the scale readings of the wagon weights recorded at the four-hour intervals. The calculated weight-loss curve was plotted with the actual weight-loss curve against time. Initially, the calculated weight-loss curve compared quite closely with the actual weight-loss curve, the calculated loss being somewhat less than the actual loss. During the latter periods of the cycle, the calculated losses were much higher than the actual losses measured. The reason for this could center around a defective exhaust dew cell. Initially, more water was evaporated than calculated because of the heat of respiration produced by the wet mass. During the latter stages of the cycle,
more and more heat was being used to elevate the temperature of the mass, while less and less was being used to evaporate moisture. Perhaps the dew cell was not sensitive enough to these changes. Air flow calculations could be off slightly because the orifice plates were not calibrated for a discharge coefficient. However, this would tend to give a curve that paralleled the actual curve, since the mass flow rate was essentially a constant. The curves do illustrate trends and also indicate that for the most part calculations were in accordance with the size of the mass studied.
Graph 12: October 10 - 11
Graph showing variation of temperatures with time.

1. Outside
2. Heated
3. Exhaust
4. Second bale
5. Third bale
6. Bottom bale
7. 400 ft. below 8
8. 600 ft. below 5
9. Second bale

Time in Hours
Graph 13.

October 10 - 11

Graph showing variation of thermal efficiency with time.

NOTE: Breaks in the graph indicate when the wagon was weighed.
Graph 14. October 10 - 11
Drying Rate

Alfalfa Hay
Third Cutting
Moisture Content 42%
Average temp. rise 38°F
Air Flow 3310 CFM
or 29 CFM per sq. ft. of floor
RUN - September 11-12

The run of September 11-12 utilized third cutting alfalfa-grass hay as the material used for drying. The starting average moisture content was 45% and the final moisture content was 18.4%. The average temperature rise through the run was 37°F. The temperature rise did vary throughout the run because of the need for stopping and starting the burner so often. Air flow was 4240 CFM total or 37 CFM per square foot of floor area. Weighings were made after each four hours of drying, explaining the breaks in the curves at these times.

The relative humidity curves, Graph #16, exhibit the same trends as noted in the October 10-11 run. The breaks in the curve are, however, more pronounced than in the October 16-17 run, possibly because of a higher moisture content material, but more likely because of the much higher drying-air temperatures.

The temperature curves, Graph #17, illustrate again the phenomenon of internal moisture movement continuing even though external surface removal had stopped. Thermocouple #11 in the second layer shows a 10 degree depression immediately following the addition of drying air, but rose quickly to its preceding value within one half hour. The third and fourth bale layers have not yet started drying at this point. In fact, bales in these two layers exhibit an increase in temperature rather than a depression. This is due to the fact that they are still very moist, and heat of respiration is supplying heat to the hay to elevate its temperature.
Number 12, located in another section of the third layer, indicates that drying has started in that part of the third layer. This indicates the variability within the mass itself; in fact, as shown earlier, each individual bale can vary in its make-up.

Following the second four-hour period, numbers 9 and 6 again show that the heat of respiration is an important factor, since the bale temperatures were elevated again at this time. Following the third four-hour period, 9 and 6 now show a depression, indicating that drying has commenced at their location. After the fourth period, the depression noted was a little greater, probably caused by the increased heated air temperature.

The exhaust air temperature rises with approximately the same slope, but at each four-hour period it is depressed and shifted to the right.

The drying rate curve, Graph #18, was affected greatly by the starting and stopping of the drying operation. The drying rate was increased immediately following the weighing operation but decreased rapidly to its original value within an hour. This was not true during the latter stages of drying. The explanation for this lies in the fact that the analysis for this run was made on the basis that evaporation took place along the heated air wet bulb line on the psychrometric chart, or adiabatic drying. Initially this method neglects the amount of heat added to the process by the heat of respiration and, during the end of the cycle, it neglects the amount removed from the air to elevate the temperature of the dry material.
The curves for the last two four-hour periods then would have the same slope but would both be depressed in actual values.

As we noted earlier, when discussing the temperature curve, the hay was at a high enough moisture content to make the heat of respiration quite important. The drying rate curve initially illustrated a constant-rate period of drying and then showed the falling-rate period. However, the drying rate, although constant, was probably somewhat higher than the value recorded because of the heat added to the drying process from the material. This would, for calculation purposes, elevate the wet bulb temperature of the exhaust air. Evidence of this is shown by the unusually low exhaust relative humidity at the start of the drying cycle. Toward the end of the cycle when heat energy was being supplied to the mass to raise its temperature, the wet bulb was depressed below the heated air wet bulb, and readings determined for moisture pick-up as somewhat higher than actual values.

This is perhaps illustrated best by the plot of the weight-loss curves, Graph #19. Initially, the calculated loss was less than the actual loss, indicating that heat for evaporation was being supplied by the material. This was not included in the calculations. The curves later cross indicating at this point that gains and losses are equal. At the end of the cycle the calculated loss is much higher than the actual loss because much heat was being used to elevate the temperature of the hay mass.
RUN - July 31 and August 1

Second cutting alfalfa hay was used for the run of July 31-August 1. The average initial moisture content was 46.2% with the final average content 17%. The average temperature rise was 30° F. and the air flow was 5600 CFM or 49 CFM per square foot of floor area. The load was weighed at four-hour intervals, explaining the breaks in the curves.

The relative humidity curves, Graph #20, illustrate the normal changes that occur during a drying run. High relative humidity supply air caused the heated air relative humidity to rise to 35% during the pre-dawn hours. The exhaust relative humidity values at start were much lower than would be expected for the initial stages of the drying scale. This was also observed in the run of September 11-12, which utilized a high rate of air flow through the mass. This would indicate that the drying air moved, too rapidly through the mass to become saturated.

The unusually high value of the exhaust relative humidity at 0720 hours was caused by a very rapid increase in supply temperature as well as the phenomenon noted before in regard to internal moisture movement.

The temperature curves, Graph #21, again depict the four-hour drying periods. Although the initial moisture content of the hay was high, the curves show that the top, second, and third layers have already begun to dry during the first four-hour period, indicating that the zone of drying is at least three bales deep.
Drying has not occurred in the bottom layer, as illustrated by curve #10. The temperature of #10 was initially higher than the other bales, and showed an increase in temperature at the weighing periods. No indication is given that drying did occur in this bale throughout the run. However, when unloading the load, about ten bales were too wet for storage, one of these was the bale containing thermocouple #10. This indicates further that number 10 was a very dense bale or was influenced by abnormal air flow patterns. Since its temperature showed the influence of heating during the loading period and before drying was started, it would then appear that number 10 was a very dense bale.

The large depression noted at 0300 hours was caused by a heat exchanger breakdown. However, it was repaired within an hour and normal drying was continued.

The drying rate curve, Graph #22, showed a very rapid falling-rate. The low value observed at 0300 hours was caused by heat exchanger failure, and the unusually high value at 0730 hours was caused by a very rapid increase in supply air temperature.

Average values were taken from the drying rate curve during the four-hour periods and used to calculate a weight loss curve, Graph #23, which was compared to the actual weight loss curve plotted from scale readings.
Since the wet bulb temperature of the heated air was used for the basis of exhaust air calculations, we again see the same trends as were noted in the run of September 11-12. Initially, the calculated moisture removed was less than the actual and during later stages of drying was more than the actual value. These values though were in close agreement, never varying more than 75 pounds from the actual determinations. This indicates that the hay received heat from respiration early, and then received heat from the air to elevate its temperature in the later periods of the cycle.

The last three hours of the run were not plotted on some of the curves because the recording instruments were not functioning properly during this period.

**RUN - July 12-13**

Only the weight loss curve, Graph #24, from the run of July 12-13 was included in this report, because the accuracy of the Foxboro instrument is doubtful for this run. The material used was second cutting alfalfa-timothy hay. Average initial moisture content was 36%. The average temperature rise of the run was 50°F. The air flow was 2760 CFM total or 24 CFM per square foot of floor area.

The weight-loss curve exhibited nearly a constant drying rate (constant slope) initially, then decreased gradually throughout the night. A slight increase in rate is illustrated by the reverse slope noted at the end of the cycle. This can be explained by the rapidly increasing supply air temperature.
The increase in temperature promoted a decrease in the heated air relative humidity, decreased the vapor pressure of the drying air, and made the vapor pressure depression between the material and the air greater; resulting in greater moisture removal from the material.

**RUN - August 15-16 (chopped)**

Although the drying installation used in these experiments was primarily for baled hay, one load of chopped alfalfa hay was dried with it. The results obtained are reported now for general comparison with the baled hay runs.

One-quarter inch mesh screening was put down on the floor of the wagon to keep the chopped material from falling through the floor openings. The material was mowed and field-cured to about 35%, windrowed, and then chopped with a field chopper utilizing a very short cut.

The moisture content of the material at the start of drying was 35% and at the close, 8%. The average temperature rise for the entire run was $42^\circ$ F., although the rise varied from $35^\circ$ to $50^\circ$ F. during the run. A high temperature limit control on the heat exchanger kept the temperature from rising above $125^\circ$ F. The air flow was 2440 CFM total or 21 CFM per square foot of floor area.

The temperature curves, Graph 25, perhaps depict best the drying process for chopped hay.

Because the high temperature limit control was functioning on the heat exchanger, the heated air temperature remained essentially
constant for the entire run. Since this is true, no dampening of
the curves was produced, this is of importance in analyzing the slopes
of the curves.

The exhaust temperature showed no signs of rising until
after the sixth hour of drying.

The striking thing about the mass temperature is that the
slope of the temperature lines, while that part of the mass is drying,
is the same for all layers. Although the mass did not dry from top to
bottom in perfect sequence, each location in the mass - once it had
started drying - continued to dry at the same rate until the heated
air temperature was reached. Curve #10, although the last to exhibit
drying, showed essentially the same slope as did all the other loca-
tions.

Although chopped hay is a uniform material, these curves
illustrate that there is quite a variation within the mass. Number 4,
while located below Number 5, dried earlier than 5. Also, numbers 4
and 5 were in the same layer as 9 and 10, but located in the front of
the wagon, and dried seven hours before these layers located in the
center section of the wagon.

The weight-loss curve, Graph #26, depicts a constant drying
rate at first and later exhibits a falling-rate period. The calculated
end value is somewhat less than the actual value, because this run was
analyzed on the basis of drying along the wet bulb temperature of the
heated air.

The exhaust relative humidity curve and the drying-rate
curve, Graph #27, for this run both show identical characteristics. Although the material was not at a very high moisture content originally, 35%, the exhaust relative humidity curve indicates that the air was near saturation for the first seven hours of drying.

The drying rate over the first seven hours was approximately 1.60 pounds of water per minute. Multiplying this value by the time gives a calculated moisture content at the end of the constant-rate period of 23%. Observing the temperatures curves, Graph #25, it can be seen that much of the material was already dry at this time.

The heat supplied curve, Graph #28, indicates that much less heat was required per pound of water evaporated with chopped hay.

The heat utilized curve remained essentially constant at 1000 Btu's per pound with a slight rise noted at the end of the cycle.

The heat supplied to the air per pound of water evaporated was approximately equal to that utilized by the material for the first five hours. In fact, the heat supplied per pound was actually less than that utilized for a short period, indicating that heat of respiration might have added the additional heat required for evaporation.
Graph 26
August 15-16
Calculated Weight-Loss Curve

Chopped Alfalfa
Second Cutting
Average Moisture Content 33%
Average Temperature Rise 42°F
Air Flow 2440 CFH or 21 CFH per square foot of floor

- Actual Scale Weight

Weight in Pounds

1400 1600 1800 2000 2200 2400 2600 2800

Time in Hours
After five hours of drying the heat supplied per pound of water evaporated gradually increased and reached a value of 3000 Btu's after 18 hours of drying. When calculated from the weight-loss curve, the average moisture content of the mass was 15% at 0100. The heat supplied per pound of water evaporated at this time was only 2000 Btu's. Comparable figures for baled hay at the same average moisture content were 5000 Btu's.

Crop Drier Characteristics

Graph 29 illustrates the heat exchanger characteristics of the crop drier.

The heat supplied to the air is a function of the mass flow rate of the air and the temperature rise given the air by the exchanger. It would appear that any direct change in one would bring a proportional change in the other with constant heat being supplied. However, this is not true as illustrated by the temperature rise curve. The reason this relationship is not linear lies in the fact that the efficiency of the heat exchanger varies with air flow.

The heat exchanger surface for this burner is a large cylindrical steel shell which houses the fire pot. Heat transfer to the passing air is accomplished through a very thin film of stagnant air surrounding the cylinder. As the velocity of the air increases, the film becomes thinner resulting in greater heat transfer. This explains why the efficiency curve, which indicates a greater efficiency at higher air flows, increases with higher air velocities.

All runs were made at a full fuel flow of approximately
2.75 gallons per hour. The supply air for combustion was controlled in such a manner that maximum heat was supplied with no smoking observed from the exhaust stack.

Assuming combustion efficiency of 75%, it is suggested that the area of the burner be increased to such an extent that 75% of the heat supplied through the fuel actually be transmitted through the air film. A common means of doing this is by adding air fins.
DISCUSSION AND SUMMARY

Utilization of high temperature drying air nearly eliminates any variation in the relative humidity of the drying air. By use of a high temperature limit control on the heat exchanger, it is possible to limit any diurnal fluctuation in temperature as well as in relative humidity. Once the drying cycle has been isolated from outside conditions, it is possible to predict the drying conditions for any system.

Moisture content of the material, temperature of the heated air, and velocity of the drying air through the mass determine the depth of the drying zone. Air moving through a baled hay mass will require a certain amount of time to pick up sufficient moisture to elevate its relative humidity to the equilibrium relative humidity of the mass, which is defined by the moisture content and temperature of the mass. With constant drying-air temperature, if the depth of the mass were increased, it would appear that the flow of air could be increased proportionately and that the zone of drying would still remain within the mass. However, since vapor pick-up by moving air is analogous to heat transfer, movement of moisture through the film existing around the surface of the material must be considered. Increased air velocity tends to tear away part of the film, decreasing the film thickness, and increasing the heat transfer rate. Since moisture removal is analogous to heat transfer, the vapor transfer will be greater with higher velocities of drying air. Therefore, the relationship between moisture content of the material, and air flow, assuming a constant
temperature, is not linear but is dependent upon the characteristics of the film surrounding the material -- providing that internal moisture movement is not limiting the supply of vapor at the surface of the material.

For the runs of September 11-12 and October 10-11, the initial drying rate is constant, indicating that the drying zone is less than the depth of the material. Initially the drying zone continues to increase in depth as drying progresses, because moisture becomes less available to the drying air, requiring the air to pass through a greater depth of the mass before reaching the equilibrium relative humidity of the material. The drying rate remains constant until the drying zone reaches the depth of the material. The drying rate must now decrease because the drying air will evaporate less and less moisture. The air flow for the run of September 11-12 was 37 CFM per square foot of floor area, the average moisture content of the material was 45%, and the drying air temperature was 105°F. During the drying cycle, the drying zone was within the mass for three hours as indicated by the drying rate. Comparing this data with the run of July 31-August 1, which utilized the air flow of 49 CFM per square foot of floor area, a drying air temperature of 105°F, and which had a moisture content of 46%, the following was found to be true: The July 31-August 1 run exhibited no constant rate period but a very rapidly decreasing rate of moisture removal. Although these materials have equal average moisture contents, and equal drying air temperatures, the drying zone for the July 31-August 1 run was apparently greater than
the depth of the hay mass because of the increased air flow rate. The run of October 10-11, whose moisture content was 42% and whose air flow was 29 CFM per square foot of floor area, the drying zone was initially within the mass with a heated air temperature of 95° F. The moisture content for the run of October 9-10 was 32%, and the air flow was 25 CFM per square foot of floor area, yet the drying zone was not within the mass, even though lower air flow was used. This would indicate that for a wagon system air flows of approximately 40 CFM should be used with 45% moisture content material, and air flows below 25 CFM per square foot of floor area should be used for material at 30%, to insure efficient drying by having the drying zone within the depth of the material. Theoretically, it would appear that the air flow should be reduced as drying progresses to keep the drying zone within the depth of the material.

Perhaps another factor which affects the drying zone is the configuration of the material within the overall mass. This is indicated best by the chopped hay run, which depicted the drying rate as constant for seven hours with an air flow of 21 CFM per square foot of floor area and an average moisture content, at the start of 35%. The long length of time that the drying zone was within the chopped material indicates that the initial drying zone is very narrow. Uniformity of the hay mass in this form allows greater transfer because all the material within the mass is treated almost identically. For baled hay some of the material within the mass is treated as a whole bale or as a dense mass within a bale. The uniformity of exposure is much less,
resulting in a total lower moisture-transfer rate. Temperature is of
great importance throughout the entire run, but of utmost importance
in the latter stages of the cycle when internal moisture movement con-
trols the drying rate. This is indicated by the drying rate curves,
in the analysis of the runs of October 16-17 and October 9-10. They
showed an increased rate at the end of the cycle when the heated air
temperature increased. Regardless of the rate of moisture transfer
at the surface, the important consideration is the movement of moisture
within the material. This is controlled by the difference in vapor
pressure between the drying air and the material. Since higher temper-
atures produce a greater difference, the internal movement should in-
crease accordingly with higher drying air temperatures.

Cessation of external drying does not immediately affect
the internal process of moisture movement, as indicated in all the
runs which were carried out on the four-hour weighing basis. However,
the way the efficiency was influenced by the length of the non-drying
period could not be determined. In some cases, a higher exhaust
relative humidity for periods up to one hour after weighing was noted.
Perhaps an intermittent drying process would be beneficial at latter
stages of drying when internal movement of moisture controls the dry-
ing rate. The importance of this phenomenon should not be overlooked
in future drying studies.

In a wagon drying system as pointed out by Mackay (15) and
Fineman (7), recirculation and reverse flow are requirements for a
high operating efficiency and a uniformly dried mass. The value of
recirculation was illustrated in the analysis of the run of October 16-17. Observation in unloading the wagons point out the fact that the top layers of the load are overdried. Often the top layers become dry in a few hours, and then are subjected to high temperatures for 12-15 more hours. Handling of these overdry bales can be a problem, if storage involved any rough handling operations.

The advantages in drying chopped hay over baled hay are best illustrated by the curves showing heat supplied to the drying air per pound of water removed. The chopped hay curves and the baled hay curves for the October 16-17 run and the October 9-10 run, show the greater efficiency of the chopped hay in utilizing the heat supplied to evaporate moisture. The reason for this can only be attributed to the form in which the material is dried. It was also noted that the weight of chopped material following drying was greater than for the three similar loads of baled hay at the same final moisture content. The reason is that the hay was chopped very short and formed a very dense uniform mass within the wagon.

Inefficient heat exchanger units account for great losses in the overall drying system. As was noted in these runs, maximum overall burner efficiency for the crop drier with high air flow rates was 50%. However, with the lower flow rates recommended, it would seem that there is an even greater need for improved heat exchangers.

Upon the basis of these investigations, the following conclusions are offered:
1. High temperature drying-air can eliminate the effects of diurnal fluctuations in temperature and relative humidity.

2. Air flows of 40 CFM per square foot of floor area are recommended for material having a moisture content of 45%. Air flows of under 25 CFM per square foot of floor area are recommended for material with moisture content of approximately 30%.

3. Heat energy supplied to the drying air per pound of water evaporated can be three times greater for baled hay than for chopped material with approximately the same moisture content.

4. Drying-air temperature is of utmost importance in controlling the drying rate of hay at low moisture content.

5. Appreciable internal moisture movement continues despite the fact that external removal of surface vapor has ceased.

6. Intermittent drying will increase efficiency, but must be considered in relation to drying time to determine practicability.

7. Moisture removal from hay at low moisture contents requires more energy than the heat of vaporization at that temperature. However, the actual value could not be determined from the data.

8. Reverse flow and recirculation are requirements for high drying efficiency and a uniformly dried mass.

9. Inefficient heat exchangers can be responsible for very low overall system drying efficiencies.
RECOMMENDATION FOR FUTURE RESEARCH

The primary limiting factor in the functioning of the experimental wagon drier is the lack of an adequate method for determining wagon weights. Presently, it is necessary to dismantle the installation and transport the wagon to and from the weighing site each time a wagon weight is desired. This is time-consuming and interrupted the drying process.

A hydraulic weight system was devised to eliminate this problem, but difficulty was incurred in trying to calibrate the pressure gages. A hydraulic fluid which is not sensitive to temperature changes must be used in this system. Incorporating this weight system into the present experimental set-up would make the unit complete.

In noting the differences between the drying of baled hay and chopped hay, it seems there is a real need for a new-type packaging machine, which could combine the superior drying characteristics of chopped hay with the good handling and feeding properties of baled hay.
BIBLIOGRAPHY


